Zhang et al. BMC Ophthalmology (2025) 25:58
https://doi.org/10.1186/s12886-025-03884-5

BMC Ophthalmology

RESEARCH

Open Access

Effect of crystalline lens decentration and tilt on visual performance in eyes implanted with bifocal or extended depth of focus intraocular lenses

Yu Zhang[1,2†], Jiaqing Zhang[1†], Chen Liang[1†], Yifan Xu[1,2], Jiaying Wu[2], Junming Wu[2], Yifan Zhang[1,2], Aixia Jin[1,2], Xuhua Tan[1*] and Lixia Luo[1*]

Abstract

Purpose To explore the potential of crystalline lens decentration and tilt as indicators for screening cataract patients for presbyopia-correcting intraocular lens (IOL) implantation.

Methods Prospective observational study. Patients undergoing phacoemulsification with bifocal (Tecnis ZMB00) or extended depth-of-focus (EDOF) (Tecnis ZXR00) IOL implantation were consecutively enrolled. The decentration and tilt of the crystalline lens and the IOL were quantified through the utilization of swept-source optical coherence tomography (SS-OCT, Casia2). Postoperative visual acuity (VA), contrast sensitivity (CS), objective optical quality, and patient-reported outcomes were assessed at a 3-month follow-up. A LOWESS (LOcally WEighted Scatterplot Smoothing) curve was employed to analyze the changes in VA, CS, and objective optical quality relative to the decentration or tilt of crystalline lenses. A further comparison of visual outcomes was conducted based on the inflection points suggested by the curves.

Results Eighty-seven patients with ZMB00 IOL and 76 patients with ZXR00 IOL were included. Multiple 6-mm internal aberrations showed a nonlinear increase with greater crystalline lens decentration. The inflection points for the steep increase were observed to be 0.28 mm for the bifocal group and 0.35 mm for the EDOF group. Beyond these points, internal aberrations such as coma increased significantly (all $P<0.01$). Patient satisfaction decreased ($P<0.01$). Moreover, the bifocal group exhibited a decline in spectacle-independence from 98.67% to 83.33% ($P=0.049$), along with a reduction in CS ($P<0.05$).

Conclusions The increased decentration of crystalline lenses compromises specific visual quality aspects in eyes implanted with ZMB00 and ZXR00 IOLs, with cut-off values of 0.28 mm and 0.35 mm, respectively.

Keywords Cataract, Intraocular lens, IOL, Presbyopia-correcting IOL, Decentration, Tilt

†Yu Zhang, Jiaqing Zhang and Chen Liang are co-first authors.

*Correspondence:
Xuhua Tan
tanxh6@mail.sysu.edu.cn
Lixia Luo
luolixia@mail.sysu.edu.cn
Full list of author information is available at the end of the article

Background

The growing patient demand for enhanced postoperative visual quality has driven the development of presbyopia-correcting intraocular lenses (IOLs) [1, 2] and expanded the metrics used to evaluate visual outcomes. These evaluations now encompass more than visual acuity (VA) at all distances, incorporating objective measures such as aberration and modulation transfer function (MTF), alongside subjective assessments like contrast sensitivity (CS), patient satisfaction, spectacle independence, and adverse visual interference [3–5]. Precise alignment of the IOL is essential for optimal visual quality. Decentration and tilt of an IOL can adversely affect visual acuity [6], increase intraocular aberration [7, 8], and reduce CS [9], thus compromising visual quality. Presbyopia-correcting IOLs, integrating diffraction and spherical aberration correction designs, among other optical features, are more susceptible to decentration and tilt than monofocal IOLs [10–16].

In our previous studies on monofocal IOLs, we identified that the decentration and tilt of the crystalline lens are key predictors of IOL decentration and tilt in patients undergoing uneventful cataract surgery [17–19]. However, the relationship between crystalline lens decentration and tilt and postoperative visual quality remains unclear. Therefore, investigating this relationship and its impact on various visual quality indicators may provide valuable insights into the preoperative criteria for presbyopia-correcting IOL implantation.

In this study, two commonly used types of presbyopia-correcting IOLs were selected for analysis: bifocal and extended depth-of-focus IOLs. The two IOLs under consideration share the same optical platform, which serves to minimize potential confounding factors such as IOL material and haptic design. Both IOLs incorporate aspheric [14], spherical aberration correction [12, 20], and diffraction [21] elements, making them more sensitive to decentration and tilt. To ensure the stability and accuracy of measurements of tilt and decentration, we employed swept-source optical coherence tomography (SS-OCT) for precise assessment of these parameters. This study aimed to explore the range of crystalline lens decentration and tilt that is suitable for the implantation of these two presbyopia-correcting IOLs.

Methods

This prospective clinical study was approved by the Ethics Review Committee of Zhongshan Ophthalmic Center of Sun Yat-sen University (Ethics No. 2019KYPJ033). All procedures followed the Declaration of Helsinki principles, and all patients provided written informed consent.

Patients

This study enrolled consecutive patients who underwent phacoemulsification combined with either a bifocal IOL (ZMB00) or an extended depth of focus (EDOF) IOL (ZXR00), performed by Dr. L.L. or Dr. X.T. at the Sun Yat-sen University Zhongshan Ophthalmic Center between March 2022 and June 2023. Patients with age-related cataracts and normal cognitive function undergoing presbyopia-correcting IOL implantation were included. IOL Selection Process: Our surgical team provided comprehensive explanations regarding the theoretical functions and limitations of the available IOL options to the patients. Subsequently, patients were encouraged to make informed decisions based on their individual visual needs and expectations. The same type of IOL was implanted in both eyes of patients. The first operated eye was selected for patients with bilateral surgery.

Patients were excluded from the study if they met any of the following criteria: (1) Presence of significant ocular pathologies affecting visual acuity, such as corneal disease, glaucoma, uveitis, or severe retinopathy. (2) Zonular instability or constant strabismus. (3) Coexistence of systemic diseases known to affect ocular health, such as hyperthyroidism. (4) History of prior intraocular surgery or trauma. (5) Underwent additional surgical procedures, such as capsular tension ring implantation. (6) Intraoperative or postoperative complications, including posterior capsule rupture, IOL dislocation, or severe posterior capsule opacification. (7) Inability to comply with examination or follow-up protocols.

Preoperative examinations

A comprehensive preoperative eye examination was performed for each patient, gathering the following information: (1) Demographic details: patient's age, gender, and medical history. (2) Ocular biometric parameters: axial length (AL), anterior chamber depth (ACD), lens thickness (LT), corneal astigmatism (ΔK), and white-to-white (WTW) were measured using the IOL Master700 (Carl Zeiss Meditec AG, Jena, Germany). (3) Angle kappa, angle alpha, 4-mm corneal high-order aberration (HOA), 6-mm corneal spherical aberration (SA), and pupil diameter under photopic and mesopic conditions, measured using the OPD-Scan III aberrometer (Nidek Co, Ltd., Gamagori, Japan).

Before the surgery, Ocular biometric parameters were consistent with previous recommendations [22–26]: 21 mm < AL < 28 mm, ΔK ≤ 1.00 D, angle Kappa ≤ 0.5 mm, 4-mm corneal HOA < 0.3 μm, 6-mm corneal SA < 0.3 μm, photopic pupil diameter > 2.0 mm and mesopic pupil diameter < 6.0 mm.

Surgical technique

All surgeries were performed by experienced ophthalmologists Dr. L.L. or Dr. X.T. strictly following the standardized steps for phacoemulsification and in-the-bag folded IOL implantation. A 2.2-mm temporal clear corneal incision, a 0.8-mm side-port corneal incision, and a 5.5-mm continuous curvilinear capsulorhexis were made. IOL power was calculated using the Barrett Universal II formula. Special attention was given to the thorough removal of viscoelastic substances both before and after IOL implantation. The IOL positioning was meticulously checked for proper centering and adjusted as needed. The positioning method was as follows: three lights—one large and two small—were visible within the patient's field of view. The patient was instructed to focus on the large light directly in front. The IOL was then adjusted so that the reflection of the large light on the anterior corneal surface aligned with the center ring of the presbyopia-correcting IOL. In other words, the visual axis was aligned to pass through the center of the IOL. Antibiotics were then administered into the anterior chamber, and the incision was closed.

Postoperatively, patients were instructed to apply Tobramycin Dexamethasone Eye Ointment (Tobradex, ALCON, USA) nightly for one week, Gatifloxacin Eye Drops (Zhuning, China) four times daily for two weeks, and Prednisolone Acetate Ophthalmic Suspension (Pred Forte, Allergan Pharmaceuticals, Ireland) every two hours for the first week, then reduced to four times daily for the second week. Starting in the third week, 0.1% Pranoprofen Eye Drops (Senju Pharmaceutical Ltd, Japan) was administered four times daily for two weeks.

Decentration and tilt measurement

Crystalline lens and IOL decentration and tilt were measured using swept-source optical coherence tomography (SS-OCT) system, (CASIA2, Tomey, Nagoya, Japan), which is designed for anterior segment imaging. To precisely and repeatably measure decentration and tilt, this system employs the corneal topographic axis as the reference, [27] considered the best reference axis for accurately assessing decentration and tilt [11, 28]. Measurements were performed under mesopic conditions (3 cd/m^2) with sufficient mydriasis (pupil size ≥ 6 mm). Each subject's eyes were examined once by an experienced operator, ensuring data of "OK" quality. Preoperative measurements were performed in Lens Scan mode and postoperative measurements were taken in IOL scan mode. The scanned images were meticulously traced by the same clinician and reconstructed in 3D space using the built-in SS2000 software.

Postoperative follow-up

At 3 months postoperatively, all patients underwent the following visual quality assessments:

(1) Visual Acuity Examination: VA was recorded and analyzed using the logarithm of the minimum angle of resolution (logMAR) under photopic conditions (85 cd/m^2). Uncorrected distance visual acuity (UDVA) and best-corrected distance visual acuity (BCVA) were measured using the Early Treatment Diabetic Retinopathy Study (ETDRS, Precision Vision, Villa Park, Illinois, USA) charts at a distance of 4 m. Uncorrected intermediate visual acuity (UIVA: 80 cm) and uncorrected near visual acuity (UNVA: 40 cm) were measured with a standard optometer light box (VA-TEST PANAL, Wehen Vision, Guangzhou, China).

(2) Contrast Sensitivity Examination: Contrast sensitivity (CS) of the operated eye, corrected for refractive error, was measured using the CSV-1000E (Vector Vision, Haag-Streit, Harlow, UK). Measurements were taken across all spatial frequencies (3, 6, 12, 18 cpd) under four standard conditions: photopic (85 cd/m^2), mesopic (3 cd/m^2), photopic/mesopic with glare (40 lx), at a distance of 2.5 m [29].

CS quantifies the subtle visual perception of the refractive system in conjunction with neurological factors [30, 31]. Specifically, low-frequency CS (3 cpd) primarily reflects visual contrast, high-frequency CS (18 cpd) primarily evaluates visual acuity, and mid-frequency CS (6 cpd-12 cpd) integrates both aspects. Daily activities such as driving, reading, and mobility necessitate a primary CS of about 3–6 cpd. However, tasks requiring fine vision demand superior high-frequency resolution, and superior low-frequency resolution is crucial for night or mesopic environments [30].

(3) Objective Optical Quality: The OPD-Scan III was used to measure modulation transfer function (MTF) and internal aberrations [32, 33].

MTF describes the optical imaging quality of the entire refractive system, independent of subjective factors, with a higher MTF value indicating a clearer image [34, 35]. MTF values included: the total MTF of the whole eye (MTF TOTAL), higher-order MTF (MTF HO), and MTF TOTAL after correction of refractive error (MTF Total CR). These indicators were expressed as the area ratio under the MTF curve of the patient's eye compared to that of a normal eye.

High-order aberrations (HOA) significantly contribute to postoperative glare, ghosting, blurred vision, and loss of nighttime visual acuity [36]. Greater HOA increases the likelihood of enduring uncorrectable visual disturbances [37]. In poorly lit environments, such as dusk and night, pupil dilation amplifies HOA, increasing the risk of adverse visual disturbances [38]. Therefore, in this study, the pupil diameter for assessing objective visual quality was set at 6 mm, the upper limit for mesopic pupil inclusion criteria. To avoid interference from pupil size, data were recorded under sufficient mydriasis (pupil size ≥ 6 mm). The study focused on changes in internal aberrations caused by complex optical designs combined with increased misalignment. Internal ocular aberrations included total aberration (0th to 8th order), total higher-order aberration (3rd to 8th order), tilt (Z-11, Z11), coma (Z-13, Z13, Z-15, Z15, Z-17, Z17), trefoil (Z-33, Z33, Z-35, Z35, Z-37, Z37), and spherical (Z04, Z06, Z08) aberrations, expressed and analyzed as root-mean-square (RMS) [33, 39].

(4) Patient-Reported Outcomes: Patients were asked to complete a visual quality questionnaire and provide feedback on satisfaction, spectacle independence, and visual interference. For patients who underwent bilateral surgery, the survey was administered three months after the second eye procedure. Before completing the questionnaire, patients were explicitly instructed to base their responses on vision without glasses in the operated eye(s) post-surgery.

Visual quality and satisfaction: The Chinese version of the Catquest 9-SF questionnaire, validated using Rasch analysis in post-cataract surgery patients, [40, 41] was used to assess the degree of difficulty in daily life and satisfaction with the surgery. The questionnaire contained 9 questions, each with 5 response options ranging from 4 for "very great difficulty/very dissatisfied" to 1 for "no difficulty/very satisfied", with an additional "cannot decide" option considered as missing data [42]. The questionnaire was evaluated as a whole, with individual analyses for two specific questions: "Satisfaction with current vision", and "Do you have difficulty seeing to perform fine work (handicrafts, woodwork, needlework, etc.)". Patients who reported "very satisfied" or "somewhat satisfied" were considered satisfied, whereas those who were "unsure", "somewhat dissatisfied", or "very dissatisfied" were considered dissatisfied. For difficulty seeing fine work, patients reporting "no difficulty" were considered to have no difficulty, while those who reported "cannot decide", "some difficulty", "great difficulty", or "very great difficulty" were considered to have difficulty [43].

Spectacle independence: Patients were asked about the frequency of spectacle independence at distance, intermediate, and near distance. Patients who reported "never" wearing glasses at a given distance were classified as having "spectacle independence", while those who reported "occasionally" or "always" were classified as having "spectacle dependence".

Visual interference (photic phenomena): Pictures from the Quality of Vision (QoV) questionnaire [44, 45] were shown to patients, who were then asked to rate the severity (none, mild, moderate, severe) of photic phenomena (glare, haloes, starbursts, blurred vision, hazy vision, distortion, double vision) and the extent to which these phenomena interfered with daily life (not at all, a little, quite, very). Patients who reported "not at all" or "a little" were considered to have no interference, while those who reported "quite" or "very" were considered to have interference.

Statistical analysis

Statistical analysis was performed using Stata SE16.0 software (Stata Corp). Visual acuity data were converted to logMAR units for analysis. Normality was evaluated using the Kolmogorov–Smirnov test and histogram. Aberration data were log-transformed to meet the normality assumption. Continuous variables were expressed as mean ± standard deviation (SD) or median with interquartile range (IQR). Independent samples t-tests were used for normally distributed variables, and Mann–Whitney U tests were used for skewed variables. Categorical variables were expressed as numbers and proportions and tested for statistical significance using the χ^2 or Fisher exact tests. The variation in visual quality parameters with lens decentration was assessed using locally weighted smoothed scatterplot (LOWESS) curves, followed by explanatory analyses based on the curves' inflection points. Differences in distance, intermediate, and near visual acuity, CS, objective visual quality, and patient-reported outcomes were compared between groups on either side of the inflection point. Binary outcome analyses considered patient-reported satisfaction, the prevalence of photic phenomena, and spectacle independence. *P*-values less than 0.05 were considered statistically significant.

Results

A total of 163 patients (163 eyes) were enrolled in the study, with 87 patients (87 eyes) with ZMB00 IOL implantation and 76 patients (76 eyes) with ZXR00 IOL implantation. Comparative analysis revealed no statistically significant differences between the two groups concerning preoperative age, gender, or various biometric parameters, as shown in Table 1. Specifically, the mean decentration and tilt of the crystalline lens were 0.14 ± 0.10 mm and 4.87 ± 1.17 degrees in the bifocal group, and 0.17 ± 0.12 mm and 4.81 ± 1.20 degrees in the

Table 1 Baseline demographic and ocular parameters

Parameters	Total	IOL Type	
n (%) / Mean (SD)		ZMB00	ZXR00
Patients, n	163	87	76
Age (yrs)	63.46 (9.25)	64.13 (8.39)	62.70 (10.13)
Male, n	72 (44.17%)	40 (45.98%)	32 (42.11%)
Right eye, n	94 (57.67%)	51 (58.62%)	43 (56.58%)
AL (mm)	23.69 (1.03)	23.59 (0.96)	23.80 (1.10)
ACD (mm)	3.14 (0.39)	3.13 (0.35)	3.15 (0.43)
LT (mm)	4.43 (0.47)	4.44 (0.48)	4.43 (0.46)
Astigmatism (D)	0.59 (0.30)	0.54 (0.27)	0.63 (0.33)
WTW (mm)	11.84 (0.44)	11.87 (0.46)	11.81 (0.42)
KAPPA (mm)	0. 28 (0. 14)	0. 27 (0.13)	0. 30 (0. 15)
ALPHA (mm)	0.42 (0.17)	0.43 (0.17)	0.42 (0.16)
Photopic Pupil (mm)	3.06 (0.50)	3.03 (0.44)	3.09 (0.56)
Mesopic Pupil (mm)	4.59 (0.77)	4.58 (0.71)	4.60 (0.84)
Pre-tilt (°)	4.84 (1.18)	4.87 (1.17)	4.81 (1.20)
Pre-decentration (mm)	0.15 (0.11)	0.14 (0.10)	0.17 (0.12)
Post-tilt (°)	4.83 (1.36)	4.84 (1.37)	4.82 (1.37)
Post-decentration (mm)	0.17 (0.12)	0.17 (0.11)	0.18 (0.12)
IOL Power (D)	20.72 (2.83)	20.83 (2.54)	20.60 (3.14)

Categorical data are presented as n (%), and continuous data are presented as mean ± SD or median (interquartile range)

AL axial length, *ACD* anterior chamber depth, *LT* lens thickness, *WTW* white to white, *IOL* intraocular lens

EDOF group, respectively. Postoperatively, the ZMB00 IOL showed a mean decentration and tilt of 0.17 ± 0.11 mm and 4.84 ± 1.37 degrees, while the ZXR00 IOL exhibited 0.18 ± 0.12 mm and 4.82 ± 1.37 degrees. No statistically significant differences were found in decentration or tilt, either between the two groups at the same time or within the same group before and after surgery. The distribution of decentration and tilt of the preoperative crystalline lens and the postoperative IOL in both eyes is shown in polar coordinate plots (Fig. 1). Both the crystalline lens and the IOL were slightly decentered toward the temporal direction and tilted toward the inferotemporal direction.

Correlations were analyzed using LOWESS curves with crystalline lens decentration or tilt as the independent variable and visual acuity, CS, and objective visual quality indicators as the dependent variables. The analysis revealed that multiple 6-mm intraocular aberrations increased with lens decentration, showing a nonlinear increasing trend that was initially flat and then became steep. The inflection points for the abrupt increase in aberrations differed between the bifocal IOL and the EDOF IOL groups, measuring 0.28 mm and 0.35 mm for preoperative decentration, respectively (Fig. 2).

Comparative analyses of visual quality metrics on both sides of the crystalline lens decentration inflection points were performed (Table 2). For the bifocal group, when preoperative lens decentration was ≥ 0.28 mm (12/87, 13.79%), the following 6 mm internal aberrations increased: total (1.023 μm), tilt (0.809 μm), higher-order (0.426 μm), coma (0.430 μm), and trefoil (0.133 μm) (all $P < 0.05$). Simultaneously, certain spatial frequency CS values declined: high-frequency CS (18 cpd) decreased by 0.312 under photopic conditions without glare, and low-frequency CS (3 cpd) dropped by 0.168 with glare. Under mesopic conditions with glare, medium- and low-frequency CS (6, 12 cpd) were also reduced by 0.151 and 0.193, respectively ($P < 0.05$). Patient-reported satisfaction significantly decreased from 96.00% (72/75) to 75.00% (9/12) ($P < 0.05$), and the incidence of photic phenomena affecting daily life rose significantly from 5.33% to 16.67% ($P < 0.05$). Additionally, the spectacle independence rate declined from 98.67% to 83.33% ($P > 0.05$) (Fig. 3).

For the EDOF group, when the crystalline lens decentration was ≥ 0.35 mm (5/76, 6.58%), the 6-mm MTF HO decreased by 7.301%. The 6-mm internal aberrations increased as follows: total (1.430 μm), tilt (1.433 μm), higher-order (0.683 μm), and coma (0.883 μm) (all $P < 0.05$). Correspondingly, patient satisfaction exhibited a substantial decrease from 95.77% (68 out of 71) to 60.00% (3 out of 5), and the prevalence of photic phenomena affecting daily life increased significantly from 5.63% (4 out of 71) to 40% (2 out of 5) (all $P < 0.05$). However, CS in the EDOF group remained stable on both sides of the inflection point ($P > 0.05$) (Fig. 3).

Conversely, when decentration exceeded the IOL's corresponding inflection point, no statistically significant differences were found in various patient indices, including distance, intermediate and near visual acuity; CS; total MTF; total MTF CR; and intermediate and near spectacle independence rates in both IOL groups, compared to the group with less decentration ($P > 0.05$).

With increasing tilt of the crystalline lens, visual acuity and CS of both IOL groups remained unaffected (Figure S2). No significant increase in aberrations was observed for the ZMB00 IOL (Figure S1-A). For the ZXR00 IOL, although aberrations increased sharply at approximately 7° (Figure S1-B), no significant difference in visual quality metrics was observed on either side of this point ($P > 0.05$).

Discussion

This prospective study examined the impact of crystalline lens decentration and tilt on visual quality following the implantation of two presbyopia-correcting IOLs, ZMB00 and ZXR00, and assessed their potential as guidance

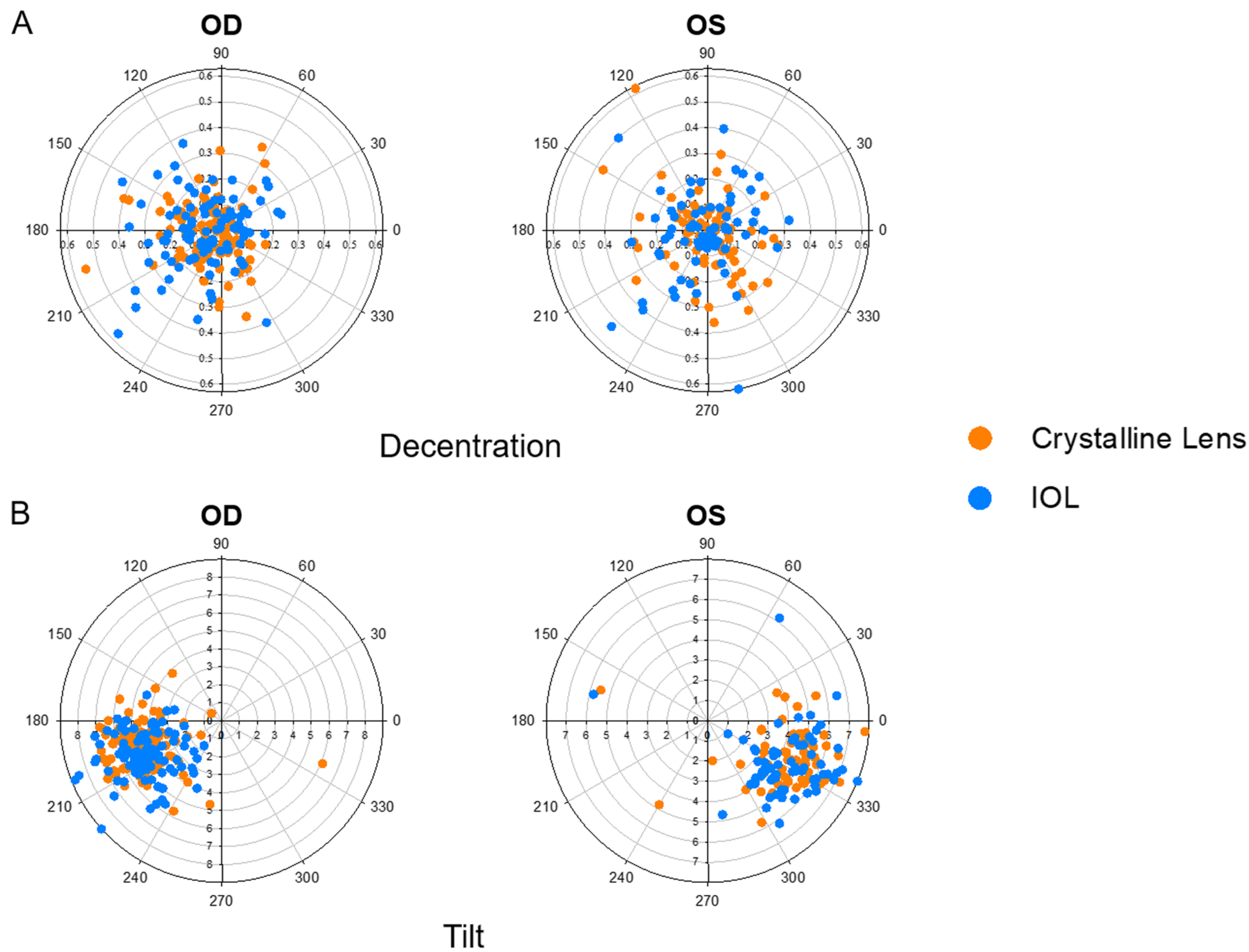

Fig. 1 Polar plots showing the decentration (**A**) and tilt (**B**) of the crystalline lens and IOL with a symmetrical distribution between the right and left eyes

for IOL implantation. Preoperative lens decentration showed superior predictive capability compared to tilt for both IOLs. Specifically, when preoperative decentration reached or exceeded 0.28 mm for ZMB00 and 0.35 mm for ZXR00, it was associated with a decline in multiple visual quality metrics. These metrics included CS at specific spatial frequencies, internal aberrations, and subjective evaluations such as patient satisfaction, spectacle independence, and photic phenomena. Our findings have clinical significance for preoperative assessment and patient counseling before presbyopia-correcting IOL implantation.

The key finding of this study is that crystalline lens decentration has a predictive effect on the postoperative visual performance of presbyopia-correcting IOLs. Crystalline lens decentration is common in cataract patients, with a mean value ranging from 0.12 mm to 0.22 mm [10, 28, 46]. Our study reported an overall mean decentration of 0.15 ± 0.11 mm, with 0.14 ± 0.10 mm for the ZMB00 group and 0.17 ± 0.12 mm for the ZXR00 group ($P > 0.05$). As the optical designs of presbyopia-correcting IOLs become more complex, accurate alignment becomes critical to optimize their performance. Previously, we have identified crystalline lens decentration as the primary predictor of IOL displacement, leading to the development of a prediction model for IOL decentration and tilt [17–19]. Therefore, assessing crystalline lens decentration and tilt before cataract surgery can help predict potential postoperative visual quality issues and improve doctor-patient communication, serving as a guide for preoperative counseling and IOL selection. For cases with decentration ≥ 0.28 mm, EDOF IOLs are recommended if they align with the patient's lifestyle. Nevertheless, patients who express a strong preference for ZMB00 IOLs should be informed of the potential for increased photic phenomena and decreased contrast sensitivity under glare conditions, allowing them to set realistic expectations and adjust their lifestyle accordingly.

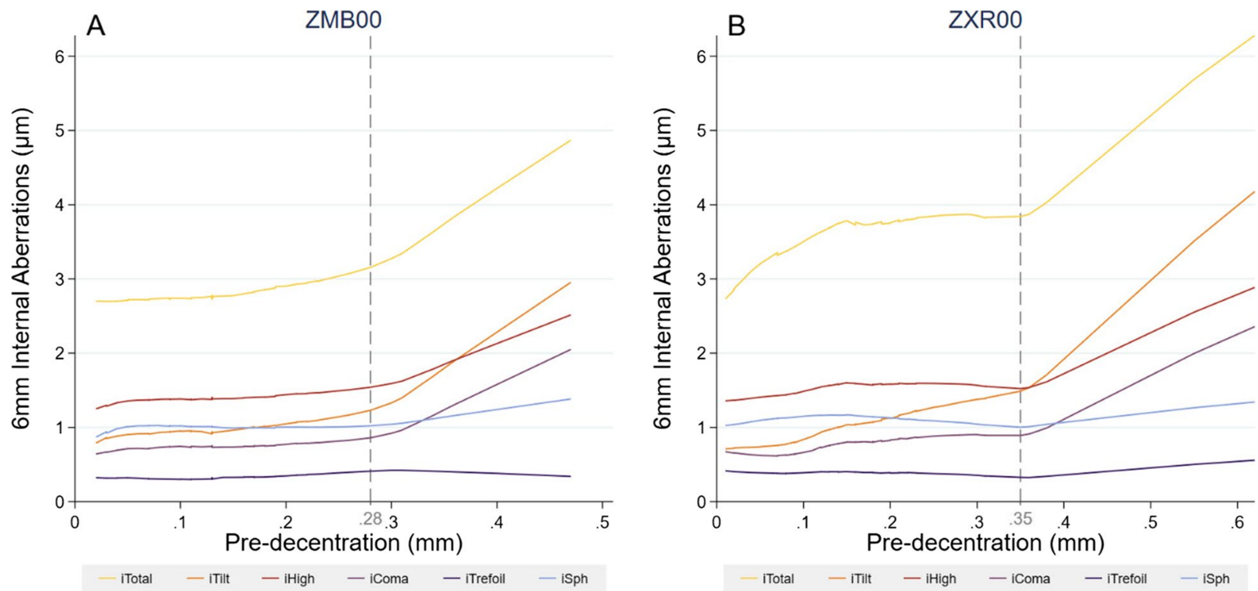

Fig. 2 LOWESS curve analysis to assess the change in internal aberrations with lens decentration for both IOLs. ZMB00 IOL (**A**) and ZXR00 IOL (**B**) both showed a nonlinear increasing trend with different inflection points

This study employs a broad range of subjective and objective indicators to sensitively detect declines in visual performance due to increased crystalline lens decentration. Previous research has shown that changes in metrics such as higher-order aberrations, MTF, and CS often occur before any noticeable decline in overall visual acuity [10, 11]. The observed changes in these indicators suggest retinal image degradation, leading to adverse photic phenomena, decreased resolution, and potential disruption of patients' neural adaptation processes [47]. In our study, as crystalline lens decentration increased, visual acuity at all distances remained stable within the observed range. However, both subjective and objective visual quality metrics were affected to varying degrees in the bifocal and EDOF IOL groups. For patients with lens decentration beyond the identified inflection points (0.28 mm for bifocal IOLs and 0.35 mm for EDOF IOLs), although both groups experienced declines in objective quality such as increased aberrations; CS remained stable in the EDOF group. In contrast, the bifocal group showed significant CS declines under both photopic and mesopic conditions with glare, indicating that decentration impacts detail resolution in glare environments more severely for bifocal IOL patients, while EDOF IOL patients adapt better to decentration. However, a notable trend emerged within the EDOF group: increased decentration correlated with a 39.44% rise in patients reporting difficulty with fine activities, a 23.38% decline in near-vision spectacle independence, and a 12.96% increase in life-affecting photic phenomena, primarily blurred vision. This suggests that, while EDOF IOLs tolerate greater decentration for certain visual functions, higher levels of decentration still adversely affect tasks requiring fine vision.

Crystalline lens tilt had less impact than decentration in our study, which is consistent with previous findings [10]. The increase in crystalline lens tilt did not result in any notable decline in visual performance among patients, suggesting that crystalline lens tilt may not be a primary consideration for cataract patients following the existing criteria. Only a few patients in the study exhibited a large tilt (greater than 7 degrees): only 3 patients, with 2 eyes in the bifocal group and 1 eye in the EDOF group. This could be attributed to the stringent patient selection criteria, which were designed to closely follow expert recommendations. Previous studies indicate that lens tilt increases with decreasing AL [48] and increasing Kappa and Alpha angles in age-related cataract eyes without a history of intraocular surgery [49]. Our study cohort comprised patients with AL > 21 mm, Kappa angle ≤ 0.5 mm, and excluded those with a history of previous pars plana vitrectomy (PPV) surgery to mitigate the potential for greater lens decentration and tilt [50]. Additionally, some previous studies used the tilt aberration of OPD-Scan III to represent the patient's true tilt, [51–53] but our study revealed a positive correlation between the true IOL decentration value measured by Casia2 and postoperative internal tilt aberration ($r = 0.48–0.6$, $P < 0.001$). Whereas the tilt value measured by Casia2 showed an unclear correlation with internal

Table 2 Visual quality changes of the two IOLs on both sides of the lens decentration inflection point

Parameters	ZMB00 Difference (0.28 mm)	ZXR00 Difference (0.35 mm)
Visual Acuity (LogMAR)		
UCVA	0.010	0.013
BCVA	0.008	−0.037
UIVA	0.053	0.002
UNVA	−0.024	−0.007
6 mm MTF (%)		
MTF Total	−2.745	−0.197
MTF HO	−1.503	−7.922*
MTF Total CR	−4.830	−2.832
6 mm Internal Aberrations (μm)#		
iTotal	1.023***	1.604***
iTilt	0.809***	1.792***
iHigh	0.426*	0.630*
iComa	0.430*	0.821***
iTrefoil	0.133	0.014
iSph	0.106	0.066
Contrast Sensitivity		
P_3 cpd	−0.143	−0.082
P_6 cpd	−0.114	0.012
P_12 cpd	−0.024	0.013
P_18 cpd	−0.312*	0.292
PG_3 cpd	−0.168*	0.088
PG_6 cpd	−0.164	0.065
PG_12 cpd	−0.003	0.042
PG_18 cpd	−0.243	0.216
M_3 cpd	−0.114	0.024
M_6 cpd	−0.087	0.039
M_12 cpd	−0.097	−0.026
M_18 cpd	−0.097	0.095
MG_3 cpd	−0.151*	0.063
MG_6 cpd	−0.193*	0.076
MG_12 cpd	−0.124	0.038
MG_18 cpd	−0.088	0.169
Questionnaire(score)		
Catquest 9-SF	0.063	0.369
Satisfaction (%)	−21.00*	−35.77*
Disturbance (%)	11.34	12.96
Fine Work (%)	−7.66	−39.44
Spectacle Independence		
Far (%)	−15.34*	2.82
Intermediate (%)	−7.00	4.23
Near (%)	6.34	−23.38

UDVA uncorrected distance visual acuity, *BCVA* best-corrected distance visual acuity, *UIVA* Uncorrected intermediate visual acuity, *UNVA* uncorrected near visual acuity, *LogMAR* logarithms of the minimal angle of resolution, *MTF* modulation transfer function, *MTF HO* MTF at high-order, *MTF Total CR* MTF Total after correcting refractive errors, In Contrast Sensitivity section errors, In Contrast Sensitivity section: *P* photopic, *PG* photopic with glare, *M* mesopic, *MG* mesopic with glare

Table 2 (continued)

* = $P < 0.05$. *** = $P < 0.001$. #: these *p*-values have been corrected for multiple comparisons

tilt aberration ($P = 0.01–0.41$) (Figure S3). Thus, the representativeness of the tilt aberration measured by OPD-Scan III for lens or IOL tilt requires further clarification by additional studies.

In selecting presbyopia-correcting IOLs, researchers aim to balance moderate loss in retinal image quality with functional gains while ensuring the stability of retinal images, particularly in cases where IOL decentration or residual refractive errors might occur postoperatively. Our study provides a reference for predicting the stability of postoperative retinal images.

We also summarize findings on the retinal image quality associated with various IOL types, aiming to provide a useful reference for IOL selection. Recent studies [1, 54] have shown that diffractive EDOF IOLs reduce the overlap between near and distant images by lowering the addition power and bringing the intermediate and distant focal points closer. This design offers better visual quality than high-add bifocal IOLs in the same patients. However, EDOF IOLs that extend the depth of focus by increasing spherical aberration do so at the cost of reduced far-focus retinal image quality.

Another series of studies [55, 56] analyzed retinal images from patients implanted with various IOLs. After excluding the effects of low-order aberrations, results indicated that trifocal IOLs with a refractive-diffractive hybrid design offered the best retinal image quality for pupil diameters of 3–4 mm. However, these IOLs were highly sensitive to residual refractive errors. Aspheric monofocal IOLs and wavefront-optimized EDOF IOLs showed comparable and stable retinal image quality. In contrast, EDOF IOLs with higher spherical aberration exhibited poorer retinal image quality. Additionally, high-addition rotationally asymmetric multifocal IOLs (e.g., +3D) and multi-zone refractive CTF IOLs introduced significant coma aberrations, resulting in the poorest visual quality."

Our study's strengths include its prospective design, comprehensive preoperative and postoperative assessments, and the use of advanced imaging technology for precise measurements. However, there are several limitations to consider. First, patients chose their IOL type based on full informed consent and their lifestyle needs; therefore, the study employed a nonrandomized controlled design. Nonetheless, the comparable preoperative baseline between the two groups helped minimize the impact of the nonrandomized design. Second, only one eye per patient was included to avoid the correlation of binocular parameters, so binocular visual quality

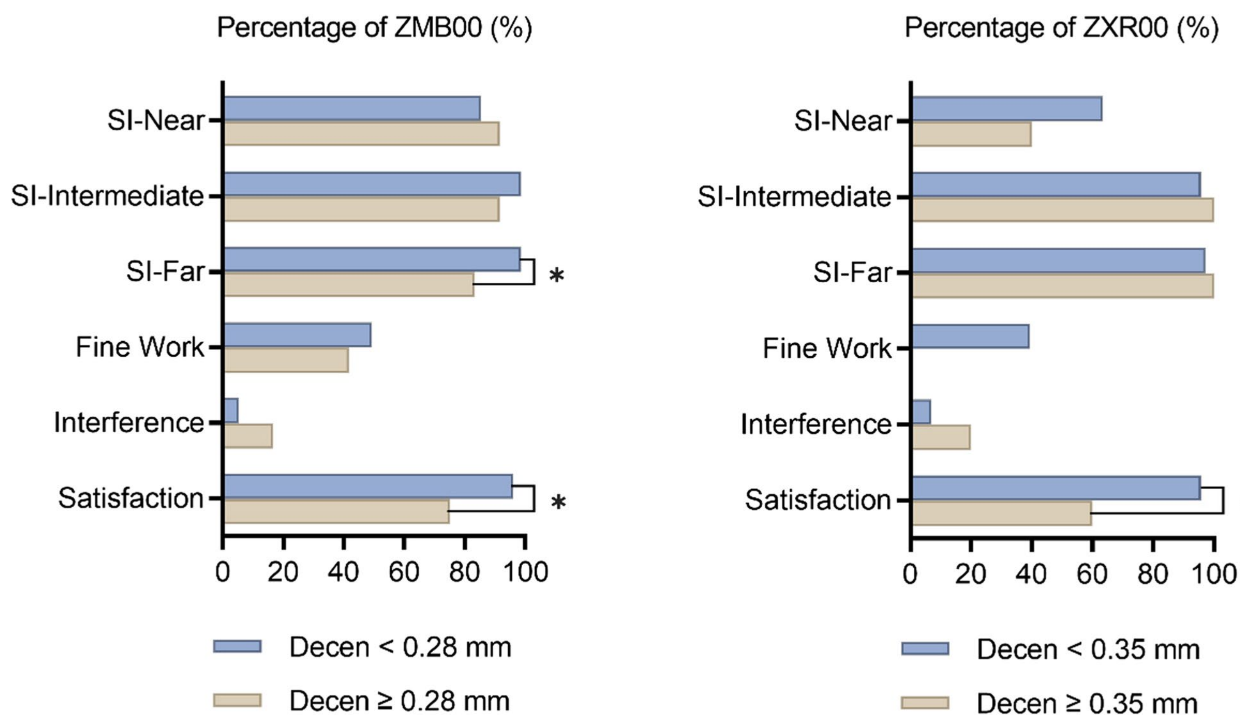

Fig. 3 Changes in the proportion of patient-reported outcome indicators on either side of the inflection points. SI = spectacle independence, Decen = decentration, * = $P < 0.05$

indicators such as stereopsis, were not assessed. Third, as a single-center study focusing on two representative presbyopia-correcting IOLs, the findings may not be fully generalizable to populations with different intraocular lenses that feature a variety of optical designs (e.g., diffractive, zonally refractive, hybrid, etc.). Moreover, the proportion of patients with significant crystalline lens decentration is relatively low in the general population, and our study population followed strict inclusion and exclusion criteria. As a result, the number of patients exceeding the observed thresholds was limited, which may influence the generalizability of our findings. In the future, we look forward to larger-sample studies to further explore and validate these results.

In this study, we found that crystalline lens decentration affects both subjective and objective visual performance after implantation of bifocal IOLs (ZMB00) and EDOF IOLs (ZXR00), with EDOF IOLs demonstrating greater tolerance to lens decentration than bifocal IOLs. Crystalline lens decentration ≥ 0.28 mm and ≥ 0.35 mm were associated with reduced visual performance in patients implanted with ZMB00 and ZXR00, respectively. Preoperative assessment of these parameters may guide IOL selection and improve postoperative visual quality. Future research should focus on refining preoperative evaluation techniques and developing strategies to further improve patient satisfaction with presbyopia-correcting IOLs.

Abbreviations

IOL	Intraocular lens
PC-IOL	Presbyopia-correcting intraocular lens
EDOF	Extended depth-of-focus
AS-OCT	Anterior-segment optical coherence tomography
SS-OCT	Swept-source optical coherence tomography
VA	Visual acuity
CS	Contrast Sensitivity
AL	Axial length
ACD	Anterior chamber depth
LT	Lens thickness
ΔK	Corneal astigmatism
WTW	White-to-white
SA	Spherical aberration
UDVA	Uncorrected distance visual acuity
BCVA	Best-corrected distance visual acuity
UIVA	Uncorrected intermediate visual acuity
UNVA	Uncorrected near visual acuity
LogMAR	Logarithms of the minimal angle of resolution
EDTRS	Early Treatment Diabetic Retinopathy Study
MTF	Modulation transfer function
MTF HO	MTF at high-order
MTF Total CR	MTF Total after correcting refractive errors
HOA	High-order aberrations
RMS	Root-mean-square
QoV	Quality of Vision
P	Photopic
PG	Photopic with glare
M	Mesopic
MG	Mesopic with glare
D	Diopter
SI	Spectacle independence

LOWESS LOcally WEighted Scatterplot Smoothing

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12886-025-03884-5.

Supplementary Material 1: Supplemental Figure 1. Correlation between crystalline lens tilt and objective visual quality assessed by the LOWESS curve. Neither the ZMB00 IOL (A) nor the ZXR00 IOL (B) in the figure shows a significant trend of change. Supplemental Figure 2. LOWESS curves to assess the correlation between decentration and tilt of the crystalline lens and contrast sensitivity. CS = contrast sensitivity. Supplemental Figure 3. Correlation of intraocular lens decentration or tilt values with 6 mm internal tilt aberration. iTilt = internal tilt aberration measured by OPD-Scan III, Post-Tilt/Decentration: Postoperative IOL tilt/decentration measured by Casia2.

Acknowledgements
None.

Authors' contributions
LL, XT, CL and YZ designed the study. YZ, JZ, CL, YX, JW, JW, YZ and AJ performed the study. YZ and JZ analyzed data and prepared the manuscript. XT and YZ acquired funding. The final version of the manuscript was read and approved by all authors.

Funding
This study was supported by the Funding by Science and Technology Projects in Guangzhou (2024A03J0245) and the National Natural Science Foundation of China (No. 82070940). The funding organization had no role in the design or conduct of this research.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This prospective clinical study was approved by the Ethics Review Committee of Zhongshan Ophthalmic Center of Sun Yat-sen University (Ethics No. 2019KYPJ033). All procedures followed the Declaration of Helsinki principles, and all patients provided written informed consent.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Author details
[1]State Key Laboratory of Ophthalmology, Zhongshan Ophthalmic Center, Sun Yat-sen University, Guangdong Provincial Key Laboratory of Ophthalmology and Visual Science, Guangzhou, China. [2]Sun Yat-Sen University of Medical Sciences, Guangzhou, China.

Received: 19 November 2024 Accepted: 22 January 2025
Published online: 03 February 2025

References

1. Megiddo-Barnir E, Alió JL. Latest Development in Extended Depth-of-Focus Intraocular Lenses: An Update. Asia Pac J Ophthalmol (Phila). 2023;12(1):58–79.
2. Rampat R, Gatinel D. Multifocal and Extended Depth-of-Focus Intraocular Lenses in 2020. Ophthalmology. 2021;128(11):e164–85.
3. Cho JY, Won YK, Park J, Nam JH, Hong JY, Min S, et al. Visual Outcomes and Optical Quality of Accommodative, Multifocal, Extended Depth-of-Focus, and Monofocal Intraocular Lenses in Presbyopia-Correcting Cataract Surgery: A Systematic Review and Bayesian Network Meta-analysis. JAMA Ophthalmol. 2022;140(11):1045–53.
4. Han X, Zhang J, Liu Z, Tan X, Jin G, He M, et al. Real-world visual outcomes of cataract surgery based on population-based studies: a systematic review. Br J Ophthalmol. 2023;107(8):1056–65.
5. Hecht I, Kanclerz P, Tuuminen R. Secondary outcomes of lens and cataract surgery: More than just "best-corrected visual acuity." Prog Retin Eye Res. 2022;5: 101150.
6. Holladay JT, Piers PA, Koranyi G, van der Mooren M, Norrby NES. A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. J Refract Surg. 2002;18(6):683–91.
7. Martínez-Plaza E, López-de la Rosa A, Papadatou E, Habib NE, Del Águila-Carrasco AJ, López-Miguel A, et al. Influence of decentration and tilt of Tecnis ZCB00 on visual acuity and higher order aberrations. Eye (Lond). 2023;37(8):1640–5.
8. He W, Qiu X, Zhang S, Du Y, Zhang Y, Lu Y, et al. Comparison of long-term decentration and tilt in two types of multifocal intraocular lenses with OPD-Scan III aberrometer. Eye (Lond). 2018;32(7):1237–43.
9. Oltrup T, Bende T, Al-Mohamedi H, Cayless A, Bende M, Leitritz MA, et al. Comparison of spherical and aspherical intraocular lenses with decentration and tilt error using a physical model of human contrast vision and an image quality metric. Z Med Phys. 2021;31(3):316–26.
10. Chen XY, Wang YC, Zhao TY, Wang ZZ, Wang W. Tilt and decentration with various intraocular lenses: A narrative review. World J Clin Cases. 2022;10(12):3639–46.
11. Ashena Z, Maqsood S, Ahmed SN, Nanavaty MA. Effect of Intraocular Lens Tilt and Decentration on Visual Acuity, Dysphotopsia and Wavefront Aberrations. Vision (Basel). 2020;4(3):E41.
12. Lawu T, Mukai K, Matsushima H, Senoo T. Effects of decentration and tilt on the optical performance of 6 aspheric intraocular lens designs in a model eye. J Cataract Refract Surg. 2019;45(5):662–8.
13. McKelvie J, McArdle B, McGhee C. The influence of tilt, decentration, and pupil size on the higher-order aberration profile of aspheric intraocular lenses. Ophthalmology. 2011;118(9):1724–31.
14. Baumeister M, Bühren J, Kohnen T. Tilt and decentration of spherical and aspheric intraocular lenses: effect on higher-order aberrations. J Cataract Refract Surg. 2009;35(6):1006–12.
15. Wang L, Koch DD. Effect of decentration of wavefront-corrected intraocular lenses on the higher-order aberrations of the eye. Arch Ophthalmol. 2005;123(9):1226–30.
16. Altemir-Gomez I, Millan MS, Vega F, Bartol-Puyal F, Gimenez-Calvo G, Larrosa JM, et al. Comparison of visual and optical quality of monofocal versus multifocal intraocular lenses. Eur J Ophthalmol. 2020;30(2):299–306.
17. Gu X, Zhang M, Liu Z, Ruan X, Tan X, Zhang E, et al. Building prediction models of clinically significant intraocular lens tilt and decentration for age-related cataract. J Cataract Refract Surg. 2023;49(4):385–91.
18. Gu X, Chen X, Yang G, Wang W, Xiao W, Jin G, et al. Determinants of intraocular lens tilt and decentration after cataract surgery. Ann Transl Med. 2020;8(15):921.
19. Chen X, Gu X, Wang W, Xiao W, Jin G, Wang L, et al. Characteristics and factors associated with intraocular lens tilt and decentration after cataract surgery. J Cataract Refract Surg. 2020;46(8):1126–31.
20. Park S, Kim MJ, Kim KH. In vitro optical performance of multifocal and extended depth-of-focus intraocular lenses in spherical aberration conditions. J Cataract Refract Surg. 2022;48(5):616–22.
21. Schmid R, Luedtke H, Borkenstein AF. Effect of decentration and tilt on four novel extended range of vision intraocular lenses regarding far distance. Eur J Ophthalmol. 2023;33(2):933–42.
22. Romano V, Madrid-Costa D, Alfonso JF, Alio J, Allan B, Angunawela R, et al. Recommendation for Presbyopia-Correcting Intraocular Lenses: A Delphi Consensus Statement by the ESASO Study Group. Am J Ophthalmol. 2023;253:169–80.
23. Yao K, Bi H, Chen W, Lu Y, Tang X, He S. Expert consensus on the clinical application of multifocal intraocular lenses in China. Zhonghua Yan Ke Za Zhi. 2019;55(7):491–4.
24. Braga-Mele R, Chang D, Dewey S, Foster G, Henderson BA, Hill W, et al. Multifocal intraocular lenses: relative indications and contraindications for implantation. J Cataract Refract Surg. 2014;40(2):313–22.

25. Montrimas A, Žemaitienė R, Yao K, Grzybowski A. Chord mu and chord alpha as postoperative predictors in multifocal intraocular lens implantation. Graefes Arch Clin Exp Ophthalmol. 2024;262(2):367–80.
26. Yeu E, Cuozzo S. Matching the Patient to the Intraocular Lens: Preoperative Considerations to Optimize Surgical Outcomes. Ophthalmology. 2021;128(11):e132–41.
27. Chang DH, Waring GO. The subject-fixated coaxially sighted corneal light reflex: a clinical marker for centration of refractive treatments and devices. Am J Ophthalmol. 2014;158(5):863–74.
28. Li Z, Zhu Z, Li X, Meng Z, Qu W, Zhao Y. Age-related changes in crystalline lens tilt and decentration: swept-source OCT study. J Cataract Refract Surg. 2021;47(10):1290–5.
29. Richman J, Spaeth GL, Wirostko B. Contrast sensitivity basics and a critique of currently available tests. J Cataract Refract Surg. 2013;39(7):1100–6.
30. Zimmerman AB, Lust KL, Bullimore MA. Visual acuity and contrast sensitivity testing for sports vision. Eye Contact Lens. 2011;37(3):153–9.
31. Yamaguchi T, Negishi K, Ohnuma K, Tsubota K. Correlation between contrast sensitivity and higher-order aberration based on pupil diameter after cataract surgery. Clin Ophthalmol. 2011;5:1701–7.
32. Holzer MP, Goebels S, Auffarth GU. Precision of NIDEK OPD-scan measurements. J Refract Surg. 2006;22(9 Suppl):S1021-1023.
33. Barreto J, Netto MV, Cigna A, Bechara S, Kara-José N. Precision of higher order aberration repeatability with NIDEK OPD-scan retinoscopic aberrometry. J Refract Surg. 2006;22(9 Suppl):S1037-1040.
34. Campbell FW, Gubisch RW. Optical quality of the human eye. J Physiol. 1966;186(3):558–78.
35. Liang J, Williams DR. Aberrations and retinal image quality of the normal human eye. J Opt Soc Am A Opt Image Sci Vis. 1997;14(11):2873–83.
36. Schwiegerling J. Theoretical limits to visual performance. Surv Ophthalmol. 2000;45(2):139–46.
37. Henein C, Fang CEH, Bokre D, Khan M, Adan A, Bouremel Y, et al. Optical aberrations following implantation of multifocal intraocular lenses: a systematic review and meta-analysis protocol. BMJ Open. 2022;12(8):e059350.
38. Chang DH, Rocha KM. Intraocular lens optics and aberrations. Curr Opin Ophthalmol. 2016;27(4):298–303.
39. Lombardo M, Lombardo G. Wave aberration of human eyes and new descriptors of image optical quality and visual performance. J Cataract Refract Surg. 2010;36(2):313–31.
40. Lin X, Li M, Wang M, Zuo Y, Zhu S, Zheng Y, et al. Validation of Catquest-9SF questionnaire in a Chinese cataract population. PLoS ONE. 2014;9(8):e103860.
41. Adnan TH, Mohamed Apandi M, Kamaruddin H, Salowi MA, Law KB, Haniff J, et al. Catquest-9SF questionnaire: validation of Malay and Chinese-language versions using Rasch analysis. Health Qual Life Outcomes. 2018;16(1):5.
42. Lundström M, Kugelberg M, Montan P, Nilsson I, Zetterberg M, Pesudovs K, et al. Catquest-9SF functioning over a decade - a study from the Swedish National Cataract Register. Eye Vis (Lond). 2020;7(1):56.
43. Liu X, Hannan SJ, Schallhorn SC, Schallhorn JM. Angle Kappa is Not Correlated with Patient-Reported Outcomes After Multifocal Lens Implantation. Clin Ophthalmol. 2024;18:605–12.
44. McAlinden C, Pesudovs K, Moore JE. The Development of an Instrument to Measure Quality of Vision: The Quality of Vision (QoV) Questionnaire. Invest Ophthalmol Vis Sci. 2010;51(11):5537.
45. Grzybowski A, Kanclerz P, Muzyka-Woźniak M. Methods for evaluating quality of life and vision in patients undergoing lens refractive surgery. Graefes Arch Clin Exp Ophthalmol. 2019;257(6):1091–9.
46. Chen X, Gu X, Wang W, Jin G, Wang L, Zhang E, et al. Distributions of crystalline lens tilt and decentration and associated factors in age-related cataract. J Cataract Refract Surg. 2021;47(10):1296–301.
47. D'Oria F, Scotti G, Sborgia A, Boscia F, Alessio G. How Reliable Is Pyramidal Wavefront-Based Sensor Aberrometry in Measuring the In Vivo Optical Behaviour of Multifocal IOLs? Sensors (Basel). 2023;23(7):3534.
48. Shen L, Yang W, Li D, Wang Z, Chen W, Zhao Q, et al. Crystalline lens decentration and tilt in eyes with different axial lengths and their associated factors. Indian J Ophthalmol. 2023;71(3):763–7.
49. Wang L, Guimaraes de Souza R, Weikert MP, Koch DD. Evaluation of crystalline lens and intraocular lens tilt using a swept-source optical coherence tomography biometer. J Cataract Refract Surg. 2019;45(1):35–40.
50. Tan X, Liu Z, Chen X, Zhu Y, Xu J, Qiu X, et al. Characteristics and Risk Factors of Intraocular Lens Tilt and Decentration of Phacoemulsification After Pars Plana Vitrectomy. Transl Vis Sci Technol. 2021;10(3):26.
51. Hong Y, Sun Y, Liu H, Ji Y. Effect of Decentration, Rotation, and Tilt on Objective Optical Quality of Plate Haptic Toric Intraocular Lenses in the Early Postoperative Period. Transl Vis Sci Technol. 2024;13(2):19.
52. Guo D, Meng J, Zhang K, He W, Ma S, Lu ZL, et al. Tolerance to lens tilt and decentration of two multifocal intraocular lenses: using the quick contrast sensitivity function method. Eye Vis (Lond). 2022;9(1):45.
53. Liu X, Yu M, Huang Y, Li Q, Wu W. Intraocular lens tilt and decentration after cataract surgery with and without primary posterior continuous curvilinear capsulorhexis. J Cataract Refract Surg. 2023;49(5):492–8.
54. Xiong T, Chen H, Fan W. Comparison of bilateral implantation of an extended depth of focus lenses and a blend approach of extended depth of focus lenses and bifocal lenses in cataract patients. BMC Ophthalmol. 2023;23(1):476.
55. Alio JL, D'Oria F, Toto F, Balgos J, Palazon A, Versaci F, et al. Retinal image quality with multifocal, EDoF, and accommodative intraocular lenses as studied by pyramidal aberrometry. Eye Vis (Lond). 2021;8(1):37.
56. Al-Amri SAJ, Alio JL, Milan-Castillo R, D'Oria F, Martinez-Abad A, Yebana P, et al. Clinical Retinal Image Quality of a Non-diffractive Wavefront-Shaping Extended Depth of Focus (Vivity) Intraocular Lens. J Refractive Surg. 2023;39(2):103-+.

Publisher's Note